The Role of Binaries in the Dynamical Evolution of Globular Clusters

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Abstract.

Three important developments are vastly increasing our understanding of the role of binaries in the dynamical evolution of globular clusters. From the observational side, the Hubble Space Telescope has shown us detailed pictures of the densest areas in post-collapse cluster cores. From the computational side, the Grape-4 special-purpose hardware is now allowing us to model small globular clusters on a star-by-star basis, and has already given us the first direct evidence of the occurrence of gravothermal oscillations in such systems. From the theoretical astrophysics side, integrated simulations are now becoming feasible that combine stellar dynamics with stellar evolution and hydrodynamics. Given these three developments, we can expect the current rapid progress in our understanding of globular cluster evolution to continue at an even higher rate during the foreseeable future. In this review an outline is given of the current status of globular cluster simulations, and the expected progress over the next five years.

1. Introduction

Star cluster dynamics is like a ballet with about a million performers, but it is the binary stars which take center stage, for it is in their *pas de deux* that most of the action develops. And it is through their interactions with other players, in the form of occasional *pas de trois* and *pas de quatre*, that fascinating new patterns (and even new characters) arise.

In this conference, we have already heard several talks in which the dynamics of binary stars has been reviewed, from various angles. Therefore, instead of attempting a full-fledged review, I am happy to refer to the presentations by Aarseth, Clarke, Leonard, Mardling, McMillan, Phinney and Rasio, all of whom discuss aspects of the question of how to model interactions of binary stars with their surroundings. In addition, many references to related work can be found in the review article by Hut *et al.* (1992). Given all these pointers, I will take the liberty to focus on the future more than on the past, sketching the expected developments during the next five to ten years.

In this contribution, I will first address the nature of the dynamical evolution of star clusters, in §2. Then, in the point-mass approximation, I will sketch expected developments in the purely gravitational N-body system, in §3. With the addition of effects of stellar evolution and the hydrodynamics of stellar en-

counters, more realistic modeling efforts are previewed in §4. Conclusions and a general outlook are presented in §5.

2. Ecology

Nearly everywhere in our galaxy, the local dynamics of multiple star systems and the global dynamics of the galaxy as a whole can be neatly separated. In the solar neighborhood, a double star (or triple or other multiple star system) with a diameter of a few AU will have a negligible chance to interact with neighboring stars, even on a time scale comparable to the current age of the galaxy. A rough estimate suffices here. With a density n of one star per cubic parsec, a relative velocity v of 50 km/s, and a target area σ with a radius r of 5 AU, the rate of close encounters is $n\sigma v = \pi r^2 vn = 10^{-13}/yr$. This gives a probability of only 0.1% for such an event to occur during the next Hubble time.

More distant encounters do occur of course, but a single encounter is relatively harmless, and it typically takes many encounters to unbind a wide binary (*cf.* Hut 1985 for a graphic illustration). As a result, only the widest binaries in the solar neighborhood, with separations of order $10^3 - 10^4$AU, are potentially subject to dissolution by encounters with passing stars and molecular clouds. However, even in this case the local-global interaction is a one-way street: the effect of the environment on the local system can be dramatic, but the feedback effects on the environment are negligible. A binary with a separation of 10^3 AU typically has a binding energy that is three orders of magnitude lower than the kinetic energy associated with the relative motion of single stars in the solar neighborhood. Whether or not such a binary is dissolved hardly makes a mark on the motion of the field stars. Clearly, the dynamical interactions with binaries and multiple star systems form an utterly negligible component in the energy budget of the galaxy as a whole.

Even in the densest parts of the galaxy, in the inner parsec of the galactic nucleus, the energy locked up in the internal motions of binaries is likely to be at least an order of magnitude less than the energy available in the motions of the single stars and the center-of-mass motions of the binaries and higher multiple star systems. With a velocity dispersion of more than 100 km/s, only the tightest binaries will have an orbital speed exceeding the typical center-of-mass motion, and these binaries will only contain a small fraction of all the stars in the field.

The situation is just the opposite in the case of star clusters. Both open clusters and globular clusters have a much lower velocity dispersion than the galactic center, and a much higher density than the solar neighborhood. The combined effect gives a situation in which a typical binary can easily have an orbital velocity far exceeding the velocity dispersion of the cluster, and therefore have an energy $\gg$ 1kT. Combined with the fact that observations show us that a fair fraction of the stars in clusters have been formed as binaries (*cf.* the talks during the first day of this conference, in the session 'The Search for Duplicity'), it is clear that binaries play an important role in the dynamics of star clusters.

As a result, the total energy locked up in binary binding energy is at least comparable to, and in some cases may well exceed, the total energy of the cluster as a whole (in the form of the kinetic and potential energy of the single stars

and of the centers of mass of the binaries). Given this situation, changes in binary properties that take place during the course of normal stellar evolution will have a repercussion on the dynamical evolution of a star cluster as a whole. In addition, close encounters involving a combination of single stars and binaries can affect the parameters of the binaries in very complex ways. Either type of process, internal evolution in relatively isolated binaries, or three-body and four-body encounters, will modify the balance between the two energy budgets of a cluster, governing the external and internal degrees of freedom (bulk energy and total binary binding energy, respectively).

While it is the macroscopic energy budget that drives the dynamical evolution of a star cluster as a whole, this budget can be significantly modified through the strong coupling with the comparable microscopic energy budget of internal degrees of freedom of binary stars. The feedback mechanisms between stellar dynamics and stellar evolution therefore play a vital role in the evolution of star clusters. The term 'ecology', introduced by Heggie (1992), captures the essence of this interplay.

3. The Gravitational N-Body System

Even without the complexities of mass overflow and the possibility of physical collisions in interactions between stars, the dynamical evolution of a star cluster already poses a daunting problem on the point-mass level. At the time of the conference, routine calculations of star cluster evolution typically featured a total number of particles in the range of $1 - 5 \times 10^3$, with the record being held by Spurzem & Aarseth (1996) for a run with 10^4 particles.

Why is it so hard to model a globular cluster with a more realistic number of particles, say $10^5 - 10^6$? After all, in cosmological simulations such numbers are routine these days. The problem lies in the enormous discrepancy of length and time scales in the dynamics of globular clusters. The size of a main sequence star is a factor 10^9 smaller than the size of a typical cluster. If neutron stars are taken into account, the problem is worse, and we have a factor of 10^{14} instead, for the discrepancy in length scales. The time scale on which clusters evolve, of order ten billion years, gives a discrepancy of time scales of a factor 10^{14} for Kepler orbits close to normal stars, or 10^{21} for neutron stars. As a result, globular cluster simulations are rather delicate affairs, and it is far from easy to get a code to work at all, bridging these vast scales, let alone to get a code to work efficiently (*cf.* Aarseth's contribution in these proceedings).

Currently, with routine type calculations, it is only feasible to model the evolution of a globular cluster containing roughly $N = 5 \times 10^3$ stars, since this requires some 10^{15} floating point calculations, equivalent to 10 Gflops-day, or a year or more on a typical workstation. The cpu cost scales $\propto N^3$, where the inter-particle forces contribute two powers in N and the increased time scale for heat conduction contributes the third factor of N. Therefore, a calculation with half a million stars, resembling a typical globular star cluster, will require ~ 10 Pflops-day (see Makino & Hut 1988, 1990 for more accurate scaling estimates).

While Pflops speeds are out of the question at present, it is important to note that it is only speed that is lacking now, not memory. In contrast to most other types of compute-hungry future calculations, the memory requirements for

modeling a complete globular cluster are relatively modest. All that is needed is to keep track of $N = 5 \times 10^5$ particles, each with a mass, position, velocity, and a few higher derivatives for higher-order integration algorithms. Adding a few extra diagnostics per particle still will keep the total number of words per particle to about 25 or so. With 200 bytes per particle, the total core memory requirement will be a mere 100 Mbytes.

Output requirements will not be severe either. A snapshot of the positions and velocities of all particles will only take 10 Mbytes. With, say, 10^5 snapshot outputs for a run, the total run worth 10 Pflops-day will result in an output of only 1 Tbyte, far less than what will be required by typical hydrodynamical calculations that will be carried out on a Pflops machine.

It was through these kind of considerations that a group of astrophysicists at Tokyo University decided in 1989 to begin building a series of special-purpose pieces of hardware (Sugimoto *et al.* 1990). The basic idea was to use a workstation to integrate particle orbits, while leaving the computation of the gravitational forces between the particles to the special hardware. Various versions of this GRAPE hardware have been build, and have been made available at modest cost to outside researchers as well. Price/performance ratios for these machines are far smaller than for commercially available computers, by orders of magnitude.

The name GRAPE stands for GRAvity PipE, and indicates a family of pipeline processors that contain chips specially designed to calculate the Newtonian gravitational force between particles. A GRAPE processor operates in cooperation with a general-purpose host computer, typically a normal workstation. Just as a floating point accelerator can improve the floating point speed of a personal computer, without any need to modify the software on that computer, so the GRAPE chips act as a form of Newtonian accelerator. The force integration and particle pushing are all done on the host computer, and only the inter-particle force calculations are done on the GRAPE. Since the latter require a computer processing power that scales with N^2, while the former only require $\propto N$ computer power, load balance can always be achieved by choosing N values large enough.

A significant step toward the modeling of globular star clusters has been made in the summer of 1995 with the completion of the GRAPE-4, the fastest machine to date, with a speed of more than 1 Tflops. It can be driven reasonably efficiently by a workstation of 100 Mflops. Although such a workstation operates at a speed that is lower than that of the GRAPE by a factor of 10^4, a fair fraction of the Teraflops peak speed can be reached, allowing simulations of up to 10^5 particles to reach core collapse and beyond, in the case of unequal masses (for equal masses, the maximum number of particles is somewhat lower, since those calculations are more compute intensive). The first scientific results of the GRAPE-4, including the first convincing evidence of gravothermal oscillations in N-body simulations, predicted by Sugimoto & Bettwieser (1983), have been presented at the I.A.U. Symposium 174 in Tokyo, in August 1995 by Makino (1996).

The next, and definitive step that will enable any globular cluster to be modeled realistically might take place as early as the year 2000. If funding can be found, there is no technological obstacle standing in the way of a speedup of

the current GRAPE-4 machine by a factor of a thousand, during the next five years. Most of this speed-up will come from further miniaturization, allowing a larger number of gates to be mounted on a single chip, and allowing a higher clock speed as well.

A Petaflops machine by the year 2000, allowing simulations of core collapse and post-collapse evolution of up to 10^6 particles, is thus a plausible goal. This would remove any hardware barrier towards realistic simulations of globular clusters. There would be two barriers remaining. One is the formidable task to integrate our current knowledge of hydrodynamics and stellar evolution with such large-scale stellar dynamical simulations. The other barrier concerns our current lack of knowledge of the physics of some of the processes involved in multiple-star evolution, such as common-envelope evolution.

4. The Astrophysical N-Star System

The simplest way to model a star cluster on a star-by-star basis is to approximate each star as a point mass, starting with an equal-mass system and keeping those stellar masses constant and equal throughout the calculation. While this is clearly a rather unrealistic approximation, it does allow us to model the overall behavior of a cluster, namely its core collapse and post-collapse expansion. These two phenomena are both regulated by the heat conduction provided by two-body relaxation, a process that does not require close encounters to be effective. Heat conduction, therefore, can be well described in the point-mass approximation. Heat production, however, takes place in and near the core in the post-collapse phase, and an accurate modeling of this heat engine requires a careful investigation of the physics of close binary stars, well beyond the point-mass approximation.

But even in pre-collapse calculations, the point-mass approximation quickly becomes unrealistic, as soon as we drop any of the restrictions from the simplest equal-mass calculation. For example, the inclusion of a mass spectrum in a N-body simulation will lead to mass segregation. In a real star cluster, too, most of the heavier stars tend to sink to the central area on a half-mass relaxation time scale. However, once they have arrived in the center, they do not remain there forever, since they are the first stars to burn out and loose considerable amounts of mass in their transitions to the final stage of stellar evolution. For most stars, this final stage is a white dwarf, with a mass well below that of the main sequence turn-off, which means that such a star will be expelled from the core that was dominated by its progenitors.

In contrast to the real world, a simple-minded inclusion of a mass spectrum in a N-body simulation will feature a indefinite piling-up of massive stars in the center. Of course, it is possible to repair this unrealistic situation by given the particles a finite lifetime, after which they shed a specified amount of mass, depending on their original mass. This type of recipe is the first step towards providing a simple form of stellar evolution for point particles. However, such a recipe does not specify what will happen in the case of a binary star.

For example, if two heavy core stars will form a binary in a relatively tight orbit, with a pericenter distance significantly smaller than 1 AU, it will not be possible for those stars to evolve in isolation. Instead, the heavier of the two

will undergo mass overflow onto the companion star, in a process that may or may not lead to a spiral-in and a common-envelope phase that could lead to a coalescence of the two stars. And it is precisely this type of hard binary, with a binding energy much larger than the kinetic energy of a typical single star, that plays an important role in the energy generation in the core, especially in the post-collapse phase. If the simplest stellar evolution recipes cannot handle the complexities of binary stars, there is not much point in using them at all.

The conclusion is a sobering one: as soon as we want to make an equal-mass point particle N-body simulation more realistic, we are immediately driven to add three successive refinements, namely: to include a mass spectrum; therefore to give a prescription for burn-out at finite ages; and consequently to give much more complex recipes for how binaries behave — not only in isolation, which is already a complex problem, but also during interactions in which three or more stars are involved simultaneously and dynamically.

It is not surprising that such recipes have not yet been developed to a mature stage. While finding a reasonable answer for most of the cases of interest is not too difficult, such recipes are not very useful if they give answers only in, say, 99% of the cases. A cluster simulation with 10^4 stars, and a primordial binary fraction of 10% or more, will feature many thousands of strong three-body and four-body encounters, in which collisions may take place and sudden mass transfer may be initiated. It will not be practical to have to stop the simulation, even for only 1% of those encounters, in order to study the situation in detail and give an *ad hoc* prescription.

On the other hand, a fully foolproof set of recipes is unlikely to emerge from pure thought alone. For example, in some cases two different mass-exchanging binaries will meet each other, and it will be quite a challenge to provide a fully automated prescription for what will happen in such a case. Most likely, it will require a significant amount of experimentation in the form of realistic simulations, before a reliable suite of recipes will be developed.

Several groups are currently developing such sets of recipes. One approach is to start directly with N-body simulations, adding stellar evolution prescriptions to close encounter situations. A report of such a method can be found in these proceedings, in the contribution by Aarseth.

Another approach is to model the core of a dense star cluster as a homogeneous stellar system, leaving out at first two-body relaxation effects and the overall dynamical cluster evolution, while concentrating solely on the effect of close encounters. Using the automated three-body scattering package described by McMillan in his contribution to these proceedings, Portegies Zwart has begun to implement a complete set of recipes for stellar collisions as well as stellar evolution effects, in order to model the evolution of an otherwise static cluster core (*cf.* his talk at this symposium, and Hut 1995, where an example is given of one of his calculations in the form of an interplay between three stars, leading to the formation of two blue stragglers).

5. Conclusions and Outlook

Fifteen years ago, fundamental aspects of the dynamical evolution of globular clusters were still unknown. The results of core collapse, as well as the character of the subsequent evolution, were hardly explored.

Ten years ago, several approximate treatments, such as Fokker-Planck models and conducting gas sphere models, had begun to explore the nature of post-collapse evolution, and had shown the ubiquitous presence of a new and unexpected phenomenon: gravothermal oscillations, a form of thermodynamic instability in the inner few percent of the cluster mass.

Five years ago, another major new ingredient had become common-place in cluster simulations: the presence in globular clusters of a significant fraction of primordial binaries, something that greatly affected the dynamics of the post-collapse evolution, suppressing core oscillations as long as most of these primordial binaries had not yet been destroyed or ejected.

Around the time of this conference, full N-body calculations have begun to approach the size of small globular clusters, and have already delivered hard evidence for the existence of gravothermal oscillations in realistic cluster models. At the same time, realistic simulations are starting up that include not only gravitational stellar dynamics, but also hydrodynamical effects of collisions and close encounters, as well as a host of stellar evolution effects.

What can we expect the state of the art to be around the year 2000, another five years from now? On the hardware side, if we are lucky, we may be able to extend our N-body calculations by another factor of ten in N, which will enable us to simulate all types of globular clusters on a star-by-star basis.

On the software side, we can expect to have several suites of stellar evolution recipes, integrated with stellar dynamical codes, which will allow us to make realistic simulations that include a large range of non-gravitational astrophysical effects. Perhaps some of these integrated systems will even have small and robust stellar evolution codes running in parallel with the background stellar dynamics code, in order to solve complex situations from scratch.

Finally, on the side of our understanding of fundamental physical processes, we can express the hope that current bottlenecks, such as uncertainties concerning common envelope evolution, will slowly begin to yield their secrets, as a result of ever more detailed three-dimensional hydrodynamical simulations. However, the full resolution of some of these bottlenecks is expected to take far longer than five years.

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